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Growth and provenance of a Paleozoic subduction complex in the Broken River Province, Mossman Orogen: evidence from detrital zircon ages

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Growth and provenance of a Paleozoic subduction complex in the Broken River Province, Mossman Orogen: evidence from detrital zircon ages

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Abstract

A Paleozoic subduction complex dominates the Mossman Orogen developed at the northern extremity of the Tasmanides, eastern Australia. Its southern part, displayed in the Broken River Province, is characterised by dismembered ocean-plate stratigraphy in which turbidite-dominated packages and widespread tectonic mélange development are characteristic. The Broken River complex is characterised by formations with quartzose sandstone alternating with those largely formed of sandstone of more labile character. The two compositional groups are considered to reflect separate, age-significant sedimentary regimes, but their ages have hitherto been poorly constrained. With the use of 1082 concordant detrital zircon ages from 13 samples we provide age control for the complex and track its sedimentary provenance. Of quartzose units, the Tribute Hills Arenite and Pelican Range Formation are late Cambrian–Early Ordovician, and the Wairuna Formation is Middle to Late Ordovician, in age. The more labile units (Greenvale, Perry Creek and Kangaroo Hills formations) are collectively of late Silurian–mid Devonian age. Development of the complex spanned some 130 Myr. Continent-derived sediment involved in accretion of much the complex, from mid Ordovician to mid Devonian, was largely sourced from a nearby magmatic arc of late Cambrian–Devonian age, now represented by granitoid plutons of the Macrossan and Pama igneous associations. An older far field Pacific-Gondwana sediment source is characteristic of early-phase (late Cambrian–Early Ordovician) accretion, in common with sedimentary units of this age generally developed in the Tasmanides. We consider the complex to have grown largely by underplating that positioned younger components beneath those that are older, with out-of-sequence thrust interleaving of these components occurring late in the accretionary history. A Late Devonian contractional folding and cleavage development (Tabberabberan orogenesis) is uniformly expressed across the entire complex and reflects an abrupt change in plate engagement with imposition of a compressional stress regime.

Keywords: Broken River Province; detrital zircon; magmatic arc provenance; Mossman Orogen; orogenesis; subduction accretion; subduction complex; Tasmanides

Introduction

Subduction complexes, also referred to as accretionary complexes, are characteristic rock systems of accretionary orogens (Cawood *et al.*, 2009). They are developed where ocean-plate stratigraphy, invariably disrupted by the accretionary process, has accumulated by offscaping and underplating adjacent to the leading edge of the upper plate at a consuming plate margin (e.g. Kusky *et al.*, 2013, Wakita, 2015). Their history is commonly difficult to unravel in part because of structural complexity involving zones of tectonic mélange, large-scale thrust dislocation including out-of-sequence thrusting, and internal folding. In addition, sedimentary rocks, which generally form the bulk of subduction complexes, are almost always of deep-marine facies and generally poor in recoverable fossil assemblages from which biostratigraphic ages can be extracted. As a consequence, age constraints for such assemblages from the application of traditional methods have been scant.

Development of U–Pb dating technologies readily applicable to detrital zircon now offers a new method of obtaining age constraints. The upper plate of convergent margins, in addition to leading edge accretion, also characteristically hosts a magmatic arc located further inboard and associated with elevated topography and active erosion. Thus the source of siliciclastic sediment contributing to subduction complex accretion includes debris generated from broadly contemporary uplift and magmatism. Detrital zircon age spectra from subduction complex sandstones commonly includes a prominent, in some cases dominant, cluster that reflects derivation from a magmatic arc generated by the subduction system. For example, this has proven to be the case for the succession of subduction complexes represented in the Japanese islands (Isozaki, Akoli, Nakama, & Yanai, 2010), the Chugach complex of southern Alaska (Amato & Pavlis, 2010), the Franciscan complex of California (Dumitru, Ernst, Hourigan, & McLaughlin, 2015; Ernst, 2015) and the subduction complex developed in the New England Orogen of Australia (Korsch *et al.*, 2009). Given the general magmatic arc–subduction complex association of Cawood, Hawkesworth and Dhuime (2012), maximum depositional ages (MDA) obtained from the youngest zircon grains in populations from subduction complex sandstone samples are likely to approximate the age of deposition.

In the Silurian and Devonian, the entire Paleo-Pacific margin of Gondwana was characterised by convergent margin tectonics reflected in the widespread magmatism and orogenesis in the Tasmanides of eastern Australia (Cawood, 2005; Domeier & Torsvik, 2014; Torsvik & Cocks, 2013). The Paleozoic active margin in northeastern Australia is poorly documented in comparison to southeastern Australia. This contribution is concerned with a structurally complex assemblage of predominantly deep-marine sedimentary rocks of late Cambrian to Devonian age developed in the Broken River Province of the Mossman Orogen, northeastern Australia (Figure 1). This assemblage and its northerly continuation within the Hodgkinson Province have long been assigned a plate convergence context (e.g. Cooper, Webb, & Whitaker, 1975; Glen, 2005; Henderson, 1980; Henderson, Donchak, & Withnall, 2013) on part of the east Gondwana margin. However, the detail of its setting has been contentious. Some authors have favoured a backarc, extensional setting followed by basinal inversion (e.g. Fawkner in Arnold & Fawkner, 1980; Donchak in Henderson *et al.,* 2013, p. 302–303; Vos, Bierlein, & Phillips, 2007; Withnall & Lang, 1993), whereas others have favoured a forearc, accretionary setting (e.g. Arnold in Arnold & Fawkner, 1980; Henderson, 1987; Henderson in Henderson *et al.*, 2013, p. 299–301; Korsch *et al.*, 2012; Rosenbaum, 2018).

We summarise attributes of the assemblage, including ocean-plate stratigraphy, the widespread development of mélange zones and pervasive dislocation by thrusting. All these features are indicative of an accretionary, subduction complex setting. New data on detrital zircon ages presented here demonstrates a compelling provenance linkage between sandstone samples from the assemblage and an adjacent (inboard) belt of granitoids representing a magmatic arc. This linkage is consistent with a forearc setting for the assemblage. With the use of detrital zircon MDA from representative samples of sandstones from the Broken River Province subduction complex we resolve its broad-scale age structure and general history of accretionary development.

Geological setting

The Broken River Province comprises the southern part of the Mossman Orogen (Figure 1) at the northern extremity of the Tasmanides. The zone is a broad composite of convergent margin rock systems, which collectively form the crust for the eastern part of continental Australia (Glen, 2005; Henderson & Johnson, 2016; Rosenbaum, 2018) and once part of a bigger tract, the Terra Australis Orogen, developed on the Paleo-Pacific facing margin of eastern Gondwana during the Paleozoic (Cawood, 2005).

The province consists largely of lower to mid Paleozoic rock units divided by the Gray Creek Fault into the Graveyard Creek Subprovince in the southwest representing a forearc basin and the Camel Creek Subprovince in the east (Figure 1) containing ocean-plate stratigraphy (e.g. Kusky *et al.*, 2013), in which deep-marine siliciclastics of continental source are dominant. The Camel Creek Subprovince, representing an accretionary forearc system (subduction complex) over 100 km in exposed width (Figure 1), developed in response to subduction of oceanic crust at a continental margin (Henderson, 1987).

Paleoproterozoic to Mesoproterozoic metamorphic and plutonic rocks of the North Australian Craton lie to the west of the accretionary forearc assemblage, separated from it by a diverse mosaic of fault bounded early to mid Paleozoic crustal elements (Figure 1) with a complex composite history. The dominant element of these Paleozoic assemblages is a tract of deformed and metamorphosed Ordovician sedimentary and volcanic rocks assigned to the Greenvale Province and considered to represent the tectonised contents of a continental margin basin (Fergusson, Henderson, Withnall, & Fanning, 2007). Also represented are parts of a (?)Cambrian ophiolite assemblage (including ultramafic rocks of the Gray Creek Complex), and Late Ordovician volcanic and sedimentary rocks of the Lucky Springs Assemblage considered to be of island arc affinity (Henderson, Innes, Fergusson, Crawford, & Withnall, 2011; Henderson *et al.*, 2013). Parts of these elements are structurally intercalated into the western perimeter of the forearc assemblage.

The youngest element, the Graveyard Creek Subprovince, represents the inverted contents of a Silurian–Devonian sedimentary basin that developed on a substrate of older and more deformed rocks (Arnold & Henderson, 1976; Withnall & Lang, 1993). The basin accumulated a thick (>6 km) sequence of predominantly shallow-marine strata (Graveyard Creek and Broken River groups) in which limestone is prominent. This element has been interpreted as a forearc basin related to the subjacent subduction complex with which it overlaps in age (Henderson, 1987; Henderson *et al.*, 2013).

The southern limit of the Broken River Province is defined by the Clarke River Fault (Figure 1), on which Late Devonian sinistral translation is thought to have occurred, associated with oroclinal bending of the subduction complex rocks (Henderson, 1987; Henderson *et al.*, 2013). Rocks of the Charters Towers Province lie to the south of the Clarke River Fault. These include deformed metasedimentary rocks like those of the Greenvale Province. The Greenvale and Charters Towers provinces have been assigned to the Thomson Orogen, an early Paleozoic precursor to the mid Paleozoic Mossman Orogen in the architecture of the Tasmanides (Fergusson & Henderson, 2013, 2015; Shaanan, Rosenbaum, & Sihombing, 2018).

Hinterland to the Broken River Province subduction complex and associated forearc basin, inclusive of the Charters Towers and Greenvale provinces and the North Australian Craton, is characterised by widespread early to mid Paleozoic granitoid plutonism (Figure 1). Two age groups of these intrusions are recognised (Bultitude, Champion, & Hutton, 2013; Hutton, 2013): (1) the Macrossan Igneous Association ranging in age from late Cambrian to Middle Ordovician (510–455 Ma), and (2) the Pama Igneous Association ranging in age from Silurian to Early Devonian (435–380 Ma). The plutonic rocks exposed adjacent to the Broken River Province are predominantly granodiorite, tonalite and granite.

Deep seismic imaging indicates that Paleozoic rocks at the western margin of the Broken River Province are underlain at a depth of some 12 km by Proterozoic crust of the North Australian Craton (Korsch *et al.*, 2012). As these authors note, the north Queensland sector of continental margin has had an enduring history of compression and restructure. Fault truncation of the Broken River forearc basin by the Clarke River Fault to the south (Figure 2) shows that large-scale restructuring persisted into the mid Paleozoic. Truncation of the basin to the north suggests westward thrust displacement of the subduction complex on the Burdekin Fault to bring it directly into contact with rocks of the Greenvale Province (Henderson *et al.*, 2013).

Characteristics of the subduction complex

The suite of rocks within the complex is closely alike in lithology, sedimentary facies and structural and metamorphic attributes. They have been mapped as six formations in which sandstone is dominant, based on lithological character and its continuity as demonstrated by regional mapping (Withnall & Lang, 1992, 1993). Stratigraphic succession within formations is not resolvable and stratigraphic relationships between them are unknown because of structural complexity. Discrimination of formations rests largely on framework grain composition of sandstones with quartz-rich units (Tribute Hills Arenite, Pelican Range and Wairuna formations) mapping as alternates with those that are less so (Greenvale, Perry Creek and Kangaroo Hills formations) (Figure 2). Other lithological attributes are also distinguishing features (Table 1).

Documentation of the rock assemblages is from Arnold (1975), Arnold and Fawkner (1980) and Withnall and Lang (1993) and our field investigations. Interlayered fine to medium, thin to thick bedded sandstone and pelite showing partial to complete Bouma sequences is characteristic of all formations and dominant in most. Intervals of thick to very thick bedded, fine to very coarse sandstone are also common to most formations and dominant in the Tribute Hills Arenite. Intervals that are dominantly pelite and siltstone also occur. Medium to thick beds of polymict, pebble to cobble conglomerate are a minor lithology, best represented in the Kangaroo Hills Formation where clasts include quartz, chert, reworked sandstone, fossiliferous limestone, granitoid and minor felsic volcanic rocks. The Perry Creek Formation is characterised by scattered blocks and lenses of limestone, the largest 4 km by 500 m. Fossil contents show they range from Late Ordovician to mid Silurian and they are interpreted as olistoliths derived from an upslope shelf, transported by gravity into a deep-marine setting (Sloan *et al.*, 1995). The siliciclastics represent a deep-marine sedimentary apron emplaced largely by turbidity current and other mass flow mechanisms. We interpret them as sand-dominated, trench-wedge proximal and distal submarine fan deposits.

No fossils are known from the quartz-rich units but Withnall and Lang (1993) speculated that they are likely to be of Ordovician age based on the age of a graptolite from the lithologically matching Judea Formation in the Graveyard Creek Subprovince and similarities to Ordovician quartz-rich turbidites in the Lachlan Orogen (Veevers, 1984). Basaltic lenses are represented in most formations, although rare in the Kangaroo Hills Formation and lacking in the Tribute Hills Arenite. In many cases these are massive aphanitic bodies but pillowed, amygdaloidal, and less commonly brecciated lithologies are also represented. The lenses range from 10's of metres long and a few metres thick to 40 km in length and 1.5 km thick. Reconnaissance geochemistry for the mafic assemblage (Withnall & Lang, 1993 and A. J. Crawford unpublished data) indicates that it is of oceanic association (Figure 3; Supplementary paper 1). Intercalated chert lenses, ranging to 50 m in thickness, are also a characteristic part of the subduction complex assemblage. Many occurrences are associated with basalt. Others are not, but are likewise inferred to have been emplaced by imbrication. Poorly preserved radiolarian relicts have been noted for some.

Coherent sedimentary packages dominate all six formations. However, the disruption of bedding to form zones of tectonic mélange is also common. Such zones were considered by Arnold and Fawkner (1980) and Withnall and Lang (1993) to most likely have been developed during thrust imbrication of the complex.

Many mélange zones show a graduation from coherent strata, first to boudinage of sandstone beds interlayered with mudstone, progressing to complete dislocation of sandstone as blocks in a scaly mudstone matrix (Type 1 mélange of Cowan, 1985). Others have abrupt boundaries, generally coplanar with adjoining coherent strata. Rare chert and basalt mélange, and polymict examples also occur. Blocks are invariably elongate in the generalised plane of mudstone fabric and commonly show pinched ends. Sporadic blocks shaped as small rootless folds are widely developed. Mélange is distributed throughout the complex in zones that are commonly 1–10 m across. Larger zones also occur, ranging to over a kilometre in width. Folds with axial planar slaty cleavage affect mélange fabric in some zones.

Strain in mélange zones is shown by extensional boudinage of sandstone beds, achieved through grain boundary sliding followed by the development shear fractures that separated blocks in a mudstone matrix. As shown by Fagereng (2013), a local extensional stress regime may be expected within low-angle shear zones as developed near the base of subduction complexes. Kusky and Bradley (1999) and Mukoyoshi *et al.* (2009) have documented similar extensional shear bands for mélange zones developed within the body of a complex. For the case at hand, mélange development generally occurred when the lithification of sandstone beds was incomplete but more advanced than for mudstone, which retained low strength and the capacity for flow to fill extensional fractures (see Cowan, 1985). The vein population and vein/fracture geometries generated at deep levels in subduction complexes (e.g. Fagereng & Harris, 2014; Ujiie, 2002; Vannucchi, Remitti, & Bettelli, 2008) are lacking. We therefore consider mélange in the Broken River to have in general formed at relatively shallow levels, most likely near the toe of the complex as it developed. However, some mélange development within the shear regime of thrust zones deeper within the complex is also likely.

Pre-slaty cleavage folding is widespread, represented by sporadic, irregular, commonly tight to isoclinal, mesoscopic structures and also by rare, local zones of chaotic folding. Cryptic early deformation folds at the scale of 10's of metres have been recognised from detailed across strike traverses documenting bedding/cleavage relationships and younging determined from graded bedding that are inconsistent with structures formed by later folding with axial planar slaty cleavage. Small-scale bedding parallel faults that deviate to transect bedding are common, in some cases generating mesoscopic duplex structures. Arnold and Fawkner (1980) considered that such structures reflect strain associated with thrust imbrication as the complex developed.

Folding of similar style is common to all six formations, overprinting the earlier structure (Figure 4). It is associated with weak, variably developed, subvertical penetrative cleavage, widely developed in pelite, intersecting bedding at a low angle (Arnold, 1975; Withnall & Lang, 1993). Mesoscopic folds generated by this event are common and in general steeply plunging (Figure 4), suggesting that bedding was already steeply inclined prior to slaty cleavage folding. Larger folds of kilometre scale also occur but are uncommon; fold geometries are asymmetric, with a dominant limb. As a consequence, the younging of beds is predominantly to the western margin of the complex (Withnall & Lang, 1993; Figure 4). Associated regional metamorphism is within the chlorite zone and Kübler index-white mica b-cell dimension data for pelites indicates low to intermediate pressure temperature conditions (Brime, Talent, & Mawson, 2003).

The association of deep-marine siliciclastics, oceanic basalt, and chert representing oceanic pelagic sediment is characteristic of ocean-plate stratigraphy. These lithologies of contrasting continental and oceanic source are offscraped to form subduction complexes developed at active continental margins (Kusky *et al.*, 2013) where its integrity may be substantially disrupted by reworking as a consequence of its accretion (Wakita, 2015). Mélange zones interlayered with packages of coherent strata are characteristic of subduction complexes, especially those which are dominated by continent sourced sediment (Meneghini, Marroni, Moore, Pandolfi, & Rowe, 2009).

Samples and analytical methods

Thirteen samples were selected to provide maximum depositional ages and provenance information for the six formations recognised for the subduction complex (Figure 2; Table 1). An additional sample, from a sandstone unit (Shield Creek Formation) of the adjacent forearc basin was also analysed to provide a comparison of provenance. A felsic volcanic clast from a conglomerate in the Kangaroo Hills Formation provided a crystallisation age.

For each sample zircon grains were randomly hand-picked following crushing, density and magnetic separations, mounted in epoxy resin, polished to expose their mid-sections then imaged by cathodoluminescence to reveal zoning and imperfections as a guide to site selection for laser ablation. U–Pb isotopic analyses of zircon grains were completed in the Advanced Analytical Facility at James Cook University (Townsville) by LA-ICPMS using the equipment and methodology detailed in Shaanan, Rosenbaum and Wormald (2015) and Tucker, Roberts, Henderson and Kemp (2016). GJ-1 was used as the primary standard (609 Ma; Jackson, Pearson, Griffin, and Belousova, 2004) and an in-house Temora secondary standard (416.8 Ma; Black *et al.*, 2004).

Data processing for LA-ICPMS analyses used GLITTER software (see Jackson *et al.*, 2004) with application of a linear fit to data from the primary standard. The use of sample-standard bracketing was employed for the correction of instrumental drift over an analytical session. All ages >1 Ga are estimates from $^{238}U/^{206}Pb$ and those <1 Ga are estimates from $^{237}U/^{205}Pb$. Data from individual grains with a discordance >15% were discarded. Probability density plots and MDA extraction employed Isoplot software (Ludwig, 2003). Estimates of MDA (see Table 2 for details) employed an average from a minimum of four grains within an age cluster weighted for data point errors, and in most cases being within error of each other at the 1 sigma level (Dickinson & Gehrels, 2009); exceptions are noted in results. Errors quoted for the weighted average ages are at 95% confidence. Young grain ages representing outliers disconnected from main age clusters were not considered. Among the methods for estimating MDA reviewed by Dickinson and Gehrels (2009), the approach taken here is conservative and robust.

Results and their age significance

Maximum depositional ages and age distributions obtained for the sample set from the analysis of detrital zircon are provided in Table 2 and Figures 5 and 6, which generally show grain ages <2 Ga. All samples other than NQ150 (Shield Creek Formation) also contain a small number of grains (<12) of early Paleoproterozoic and Archean age. Cumulative proportion curves of age plots of the full detrital age spectrum for each sample are given in Figure 7. For full analytical data, see Supplementary paper 2.

Wairuna Formation

Of the three sandstone samples analysed, NQ72 and NQ73 represent quartz greywacke typical of the formation whereas GC32 sampled a lithic greywacke interlayered with quartz-rich beds. Probability and cumulative distributions of zircon ages for all three samples are closely similar with the dominant cluster at *ca* 520–470 Ma indicating late Cambrian and Ordovician ages (Figures 5 and 7). A second prominent cluster is late Neoproterozoic (650–550 Ma) and a broad, minor cluster registers Mesoproterozoic ages of 1250–1000 Ma, and there are scattered analyses indicating Paleoproterozoic to Mesoproterozoic ages between 1900 and 1500 Ma.

For NQ72, the youngest 14 grains give an MDA of 465 ± 2.4 Ma and for NQ73 the youngest seven grains provide a MDA of 470 ± 3.6 Ma. The MDA for GC32, based on a grouping of 17 grains, is 453 ± 2.9 Ma. These ages suggest that deposition of the Wairuna Formation spanned much of the Middle to Late Ordovician.

In the light of these results, the Silurian (433.3 ± 4.2 Ma and 420.7 ± 5.6) maximum depositional ages based on zircon ages for two samples previously reported for this formation by Henderson *et al.* (2011) are anomalous. One sample is from a float cobble of volcaniclastic sandstone in the bed of a creek and sourced from an unknown location although drainage of the creek is entirely within the mapped distribution of the Wairuna Formation. The second is a felsic volcanic clast from a conglomerate bed. As neither of these lithologies had been previously recorded for the Wairuna Formation but are characteristic of the adjoining Greenvale Formation to the east, Henderson *et al.* (2011) suggested that the Wairuna Formation as presently mapped may represent a structurally interleaved composite, with these samples perhaps derived from unmapped slivers of Greenvale Formation. This suggestion is supported by the detrital zircon age spectra determined for the Greenvale Formation in this paper. An interleaved relationship has been mapped for the volcanilithic Greenvale Formation and the Pelican Range Formation characterised by quartzose sandstone (Figure 2).

On the basis of the results presented here, and the uncertain status of previously dated samples, we reassign the MDA of the Wairuna Formation as Middle to Late Ordovician.

Pelican Range Formation and Tribute Hills Arenite

NQ78 and NQ158 sampled the Pelican Range Formation and NQ160 sampled the adjoining Tribute Hills Arenite. The samples are fine-grained quartz greywacke, typical of these formations (Withnall & Lang, 1993). All three provided comparable zircon age distributions with a major cluster at 550–480 Ma, significant clusters at 650–550 Ma and 1250–1000 Ma, and scattered grain ages between 1800 and 1400 Ma (Figure 6). Close similarity of these distributions (Figures 6 and 7) suggests sampling of the same sedimentary package. The three youngest grains from NQ78 provide an averaged value of

486 ± 18 Ma, inconclusive but suggestive of an early Ordovician age. For NQ158, the youngest two grain ages at *ca* 445 Ma are outliers in the distribution and dismissed on that basis. Ages for four grains give a MDA of 495 ± 6.7 Ma (late Cambrian). Rejecting one young outlier at *ca* 452 Ma, NQ160 from the Tribute Hills Formation provided a MDA of 484.4 ± 6.2 Ma (Early Ordovician) from the five youngest grains.

The ages of these units and that of the Wairuna Formation indicate that deposition of a sedimentary assemblage characterised by quartzose turbidites persisted from the late Cambrian into the Middle Ordovician. Sandstone of more labile character appeared sporadically in the Late Ordovician, broadly coeval with the Lucky Springs Assemblage, considered to be structurally interleaved with the Wairuna Formation and of island arc affinity (Henderson *et al.*, 2011), and is characteristic of Silurian and Devonian units.

Greenvale Formation

Zircon age distributions for two samples of lithofeldspathic greywacke (NQ76 and NQ156) typical of this unit are closely comparable with a dominant cluster between 500 and 400 Ma and secondary clusters between 650 and 530 Ma and 1250 and 900 Ma and a scattering of Paleoproterozoic to Mesoproterozoic from *ca* 1800 to 1400 Ma (Figure 5). Within the dominant cluster, NQ76 shows two main peaks at *ca* 445 and 420 Ma and based on the six youngest grains has an MDA of 414.6 ± 3.8. For NQ156 a MDA of 418 ± 5.8 Ma was obtained from 5 grains. An age range close to the Silurian–Devonian boundary is indicated for the Greenvale Formation, also taking into account the samples that were dated from the mapped outcrop area of the Wairuna Formation by Henderson *et al.* (2011, see above).

Perry Creek Formation

Analysis of NQ21 from the Perry Creek Formation was less conclusive. However, the age profile is distinctive, consistent with this unit being distinct from the adjacent Greenvale and Kangaroo Hills formations (Figure 5). It shows a prominent broad cluster from *ca* 510 to 375 Ma with the most striking peak at *ca* 430 Ma. The frequency distribution for older grains is similar to that shown by samples from the Greenvale and Wairuna formations. The youngest five grains give a weighted average age of 388 ± 13 Ma indicating a Devonian age although the analyses included are not within error at the 1 sigma error. This formation contains fossiliferous limestone olistoliths of latest Ordovician and mid Silurian age (Sloan *et al.*, 1995) and considerably older than the MDA. From the detrital zircon evidence the formation is likely to be Devonian, but its age is not closely constrained.

Kangaroo Hills Formation

Four widely spaced feldspathic greywacke samples spread across the broad distribution of this unit were analysed (Figure 2). They show similar age patterns with a prominent cluster at 500–400 Ma (Figure 5). Compared to other units, populations of Mesoproterozoic and older grains are much reduced (Figure 7). NQ159 from the western part of the formation shows a prominent peak at *ca* 460 and has an MDA of 427.6 ± 8.1 Ma, based on the youngest four grains. NQ85 and NQ88 were collected from the central part of the Kangaroo Hills Formation distribution. NQ85 shows a prominent peak at *ca* 450 Ma and has an MDA of 381 ± 10 Ma from the five youngest grains with one young outlier rejected. However, the analyses included do not overlap at 1 sigma level. For NQ88, a more robust MDA of 400.6 ± 3.8 Ma was obtained, based on 5 grain analyses with an anomalously young outlier grain analysis rejected. NQ89 was collected from the eastern part of the Kangaroo Hills Formation. It shows a prominent peak at *ca* 445 Ma and has an MDA of 424.3 ± 4 Ma from eight grains with one anomalously young outlier analysis rejected.

IWCR336 is a felsic volcanic clast from a polymict conglomerate horizon stratigraphically close to the sandstone interval from which NQ159 was collected. Of 20 grains analysed, 15 gave concordant results with inheritance showing in the age spectrum. The analyses show a skewed cluster with a peak at *ca* 470 Ma. The six youngest grains provided an age of 470 ± 3.9 Ma, which is taken as the crystallisation age of the volcanic parent. The clast was therefore sourced from volcanic rocks that are much older than the conglomerate itself.

Based on these results, deposition of the Kangaroo Hills Formation spanned from late Silurian to Middle Devonian. This is consistent with biostratigraphic control from limestone clasts in conglomerates. Withnall and Lang (1993) recorded long-ranging corals of late Silurian to Early Devonian age and along with Sloan *et al.* (1995) noted Early Devonian conodonts. Arnold (1975) recorded an Early Devonian coral fauna.

Commented [CF1]: Crossing this out changes the meaning and omits the fact that Withnall & Lang also recorded Early Devonian conodonts – it implies they only recorded corals. Please leave as is – Bob & Chris.

Shield Creek Formation

NQ150 is representative of coarse feldspathic sandstone characteristic of this unit, a lithology for which a plutonic provenance is implied. Modal analyses reported by Withnall and Lang (1993) record only a trace representation of volcanic detritus. Its zircons are euhedral to subhedral and most show close zoning. The age distribution obtained for this sample has a strongly dominating bimodal cluster between 500 and 400 Ma, matching the age distribution of detrital zircon from the Greenvale, Perry Creek and especially Kangaroo Hills formations, with peaks at *ca* 470 Ma and *ca* 415 (Figures 5 and 7). Significantly no Proterozoic grain ages show in the analyses in spite of the close proximity of the North Australian Craton to the Graveyard Creek Subprovince, which hosts the Shield Creek Formation, common also to samples from the Kangaroo Hills Formation (Figure 7). The youngest four grains give an MDA of 411.5 ± 5.5 Ma.

Biostratigraphic data for limestone intervals within this unit provide tight age control for it (Mawson et al., 1988; Yu & Jell, 1990). It spans the Lochkovian–Pragian boundary placed at 410.8 ± 2.8 Ma (Cohen, Finney, Gibbard, & Fan, 2013), consistent with the MDA from detrital zircon obtained in this study.

Commented [AA2]: No reference – This should be Mawson et al., 1988 – in reference list

Sandstone provenance

A provenance linkage to igneous rocks of the Macrossan and Pama Igneous associations (510–380 Ma, Bultitude *et al.*, 2013; Hutton, 2013) exposed on the margins of the Broken River Provence (Figure 2), is apparent for samples from units of mid Ordovician–Devonian age (Wairuna, Greenvale, Perry Creek and Kangaroo Hills formations). The dominant age cluster for samples from all four formations (Figure 5) matches that of the adjacent igneous rocks. The same age distribution applies to the sample from the Shield Creek Formation within the adjacent forearc basin (Figures 5 and 7).

The dominant detrital age distribution mode for nine of the eleven samples is between 470 and 450 Ma indicating that the igneous episode now represented by plutons of the Macrossan Igneous Association (Hutton, 2013) was the main sediment source of these formations including their younger (Devonian) parts. The *ca* 464 Ma clast from a Kangaroo Hills Formation conglomerate shows that felsic volcanic rocks were involved. We note that in addition to plutonic rocks of the Macrossan Igneous Association (Figure 1), volcanic rocks of Cambrian and Ordovician age are extensively represented in the Greenvale and Charters Towers provinces (Fergusson & Henderson, 2013). Representation of the younger Pama Igneous Association is strongest in Devonian samples (NQ85, NQ88). Sedimentary petrography and detrital modes reported by Withnall and Lang (1993) indicate that a volcanic component became less abundant from deposition of the Greenvale Formation deposited close to the Silurian–Devonian boundary to deposition of the younger Devonian strata of the Perry Creek and Kangaroo Hills formations consistent with progressive uplift and exhumation of a plutonic/high-grade metamorphic terrain (Withnall & Lang, 1993, p. 33–34). Nevertheless, the scarcity of Proterozoic zircons in the Kangaroo Hills Formation (Figures 5 and 7) indicates that basement rocks were not a source for this unit in contrast to older units.

The inboard magmatic arc linkage for the Broken River subduction complex demonstrated here is similar to that documented from detrital zircon studies for the Franciscan complex of California (Dumitru *et al.*, 2015; Ernst, 2015) and subduction complexes of southern Alaska (Amato & Pavlis, 2010; Davidson & Garver, 2017) and Japan (Isozaki *et al.*, 2010).

The age spectrum shown by samples from units of late Cambrian–Early Ordovician age (Tribute Hills Arenite and Pelican Range Formation) is different. Although a cluster registering provenance from the Macrossan Igneous Association is represented, the distributions are dominated by clusters in the range of 650–550 Ma, with a significant cluster also at 1300–900 Ma. These two detrital zircon age groupings, commonly referred to as the Pacific-Gondwana and Grenville clusters, respectively, are characteristic of Cambrian and Early Ordovician sandstones throughout the Tasmanides and also from cratonic basins within central Australia (Fergusson, Henderson, & Offler, 2017; Glen, Fitzsimmons, Griffin, & Saeed, 2017; Purdy, Cross, Brown, Carr, & Armstrong, 2016). These sources persisted through to the Silurian and perhaps sporadically into the Devonian as shown by a minor contribution to age spectra for samples of the Greenvale and Perry Creek formations. As noted by these authors, the Pacific-Gondwana source is widely considered to have been east Antarctica, which may also have supplied the Grenville source. Where a Grenville source is recognised in eastern Australian sedimentary rocks without accompanying Pacific-Gondwana zircons, it is considered to have been derived from the Musgrave Province of central Australia (Fergusson, Henderson, Fanning, & Withnall., 2007; Purdy *et al.*, 2016). Thus far-field sources fed the subduction complex during its early development.

The age spectra for the samples of the Camel Creek Subprovince, and also that for the Shield Creek Formation of the Graveyard Creek Province, show that a detrital contribution from Paleoproterozoic to Mesoproterozoic rocks of the North Australian Craton, presently positioned subjacent to the Broken River Province (Figure 1), was insignificant relative to grains of Paleozoic age (Figures 5–7). This suggests that the current distribution of rock systems to the west of the Broken River Province is not accurately representative of palinspastic arrangements during early to mid-Paleozoic time when a much broader zone of rocks of the Thomson Orogen, now represented by the Greenvale Province, was exposed to erosion. Thus a proximal source of sediment from Paleozoic igneous rocks of the Thomson Orogen was very strongly dominant over a more distal source from the craton. In contrast, a prominent cluster of grains derived from the North Australian Craton is apparent for many samples analysed for detrital zircon age signatures from the Hodgkinson Province of the Mossman Orogen (Adams, Wormald, & Henderson in Henderson *et al.*, 2013, pp. 239–241; Kositcin, & Bultitude, 2015).

Age structure of the complex

The units with sandstone of quartzose character (Tribute Hills Arenite, Pelican Range Formation and Wairuna Formations) are of late Cambrian to Ordovician age whereas those of more labile character (Greenvale, Perry Creek and Kangaroo Hills formations) are of late Silurian and Devonian age. Zircon age distributions differ between the two groupings (Figures 5–7). The oldest, Tribute Hills Arenite and Pelican Range Formation, show wide scatter whereas those which are younger are dominated by a <500 Ma age cluster.

Formations of different ages are structurally interleaved in the western part of the complex (Figure 2). Ages obtained for samples from the Kangaroo Hills Formation and their locations, suggest that this unit has also had its age structure complicated in a similar manner. We attribute this complexity to thrust dislocations juxtaposing parts of the complex that formed at different times. Given the uniform expression of the slaty cleavage deformation across all six formations (Figure 4), its imposition came later. Development of the age structure is shown schematically in Figure 8.

Model for accretionary development

The development of subduction complexes embraces two modes: growth by frontal accretion resulting in oceanward progradation and areal expansion, and growth by underplating, which results in thickening of the accretionary system (Cawood *et al.*, 2009; Hashimoto & Kimura, 1999; Moore & Silver, 1987) by drawing younger components beneath those already formed. Numerous factors impinge on the mode, including the nature of material at deep levels in the complex adjacent to the subduction channel and its response to shear, the kinematics and geometry of plate convergence and the supply of sediment available for accretion.

A simple steady-state outward growth has not been demonstrated from the inferred ages of deposition for well-exposed subduction complexes. Episodic growth has been demonstrated for the Chugach terrane accretionary complex of Alaska (Amanto & Pavlis, 2010) and may have also applied during accretion of the Franciscan complex of California (Wakabayashi, 2015). Age data presently available for the Broken River complex are insufficient to evaluate episodic growth. However, the across-strike width of mapped formations to which ages are attributed from detrital zircon analysis indicates that accretion was enhanced during its younger growth (some 45 Myr spanning the late Silurian–mid Devonian) compared to a similar interval of earlier growth (late Cambrian–Late Ordovician).

The architectural complexities of subduction complexes are revealed in particular by reversals in across-strike detrital zircon age patterns, inconsistent with a model of steady state, orderly accretion. Large-scale age reversals are particularly striking for the Franciscan complex where they are attributed to thrusting and folding of accretionary units (Snow, Wakabayashi, Ernst, & Wooden, 2010; Wakabayashi, 2015). They have also been documented from the Chugach-Prince Albert complex of Alaska (Davidson & Garver, 2017, figure 4), the Shimanto complex of Japan (Shibata, Orihashi, Kimura, & Hashimoto, 2008) and the Permian to Cretaceous complex of New Zealand (Adams, Campbell, & Griffin, 2017). The subduction complex of the northern New England Orogen, eastern Australia has distinctive terranes characterised by quartzose sandstones of the Shoalwater Formation (outboard) and volcaniclastic sandstones of the Wandilla Formation (inboard). This lithological distinction is not reflected in detrital zircon age spectra, which show a substantial overlap across a 40 Myr accretionary history (Korsch *et al.*, 2009), indicative of a complex age structure.

Seismic imaging shows that some contemporary subduction complexes have grown largely by underplating including those developed on the convergent margins of southwestern Canada (Calvert, 1996) and Alaska (Fuis, 1998) and adjacent to Barbados (Brown & Westbrook, 1988). The Shimanto complex of southwestern Japan developed inboard of the Nankai Trough, for which seismic interpretation is summarised by Isozaki *et al.* (2010), is a striking example of this mode of growth. The complex has a composite thickness of some 20 km and a maximum width of 100 km. Two parts of similar thickness can be discriminated across most of its width: an upper part, with northern exposure, of Early Cretaceous age and a lower part, of southern exposure and largely located offshore, assigned as Paleocene to Recent. A major thrust dislocation, the Aki Tectonic Line, separates the two parts (Isosaki *et al.*, 2010). Among well-studied, ancient subduction complexes, the Franciscan complex of Californian is considered to have grown largely by underplating (Wakabayashi, 2015).

An accretionary geometry dominated by underplating is similarly inferred for the subduction complex of the Broken River Province, with a thick slab accreted in the Silurian–Devonian underlying an older slab accreted in the Ordovician. The scale of underplating is comparable to that seismically imaged for the Shimanto subduction complex and interpreted as having applied to the Franciscan subduction complex.

Out-of-sequence thrusting, including imbrication with duplex formation is a feature of subduction complex architecture. Structure of this type has been recognised by seismic imaging in New Zealand (Barnes, 2004), Canada (Calvert, 1996) and in the Nankai Trough near southwest Japan (Moore *et al.*, 2007). Thrusting of this type has been extensively documented from surface mapping of ancient systems. Examples occur in Scotland (Fujisaki *et al.*, 2015), Costa Rica (Escuder-Viruete & Baumgartner, 2014), Sicily (Di Paolo *et al.*, 2014), Chile (Glodny *et al.*, 2005), Alaska (Gutscher, Kukowski, Malavieille, & Lallemand, 1998), California (Wakabayashi, 2017) and Japan (Hashimoto & Kimura, 1999; Ikesawa *et al.*, 2005; Ueda, Yamamato, & Terabayashi, 2016; Wakita, 2012). The dislocations involved are considered to sole onto the subduction channel at their time of formation, to be intimately associated with subduction complex growth by underplating, and to involve displacements at a range of scales in some cases many kilometres. We infer out-of-sequence thrust imbrication and duplexing to be largely responsible for intercalation of late Cambrian–Ordovician quartz-rich elements (Tribute Hills Arenite and Pelican Range and Wairuna formations) with Silurian and Devonian elements of more labile character (Greenvale, Perry Creek and Kangaroo Hills formations) within the Broken River subduction complex (Figures 2 and 8). Changes in composition of sandstone provides only a very coarse indication of the age structure in the complex, the detail of which is likely much more involved. As for other documented subduction complexes, imbrication was most likely episodic, accompanying growth of the system. The oldest large-scale imbricate dislocations are likely to have been Late Ordovician or younger, post-dating deposition of the Wairuna Formation now located at the western edge of the complex.

Terminal deformation

The consistency of slaty cleavage development and associated folding across rock units with ages spanning Ordovician–Devonian indicates that its imposition post-dated accretion of the youngest part of the Broken River subduction complex in the mid Devonian as evidenced by the MDA of sample NQ88 from the Kangaroo Hills Formation (381 ± 10 Ma). This deformation involved significant crustal shortening, thickening of the complex and the imposition of lower greenschist metamorphism on its exposed rocks. The steeply plunging character of late folds defined by bedding (Figure 4) implies that bedding was inclined prior to the slaty cleavage contraction, consistent with thrust imbrication of the complex during its growth.

Late Devonian–Mississippian cover rocks of the Clarke River Group, generally disposed in gentle open folds, are extensively developed across the Broken River subduction complex (Figure 2) with a pronounced angular unconformity separating the two rock systems. The age of deformation is constrained to *ca* 380–365 Ma. Sample NQ85 dates growth of the subduction complex as persisting into mid Devonian (385 ± 10 Ma) and the oldest conodonts from the Clarke River Group indicate an age close to the Famennian–Tournaisian boundary (Withnall & Lang, 1993) placed by Cohen *et al.* (2013) at 359 Ma. The deformation episode is also recorded in the Silurian–Devonian forearc basin, located immediately inboard of the subduction complex (Figure 2), for which a detailed biostratigraphy is published, as reviewed by Henderson *et al.* (2013). It represents a forearc basin

(Henderson, 1980, 1987) that experienced inversion with large-scale, tight folding and reverse faulting (Withnall & Lang, 1993). Conodont dating of its sequence, and that of overlapping, unconformable cover of the Bundock Creek Group, tightly constrain basin inversion as Frasnian (383–375 Ma) (Henderson *et al.*, 2013; Withnall & Henderson, 2012).

Thus geochronological constraints on slaty cleavage deformation of the Broken River subduction complex following its accretion, and inversion of the forearc basin, strongly suggest broad-scale coeval crustal contraction. For convenience this crustal contraction has been considered to represent the Tabberabberan Orogeny of widespread expression in the Tasmanides of eastern Australia (Withnall & Henderson, 2012). However, the Tabberabberan Orogeny in eastern Victoria is constrained to pre–mid to late Givetian (i.e. pre-385 Ma) and in other parts of the Lachlan Orogen in southeastern Australia is as old as 400 Ma (Fergusson, 2017) indicating diachronous deformation along the Devonian East Gondwana margin.

Fabric development and associated metamorphism has been widely reported for subduction complexes and considered to have been a progressive consequence of the accretionary process, induced by stress at deep levels as a complex developed (e.g. Hajná, Zák, Vaclav, Kachlika, & Chadimac, 2010; Meneghini *et al.*, 2009; Raimbourg, Tadahiro, Asuka, Haruka, & Kimura, 2009; Wakabayashi, 2015). In contrast, uniform regional shortening across an active margin is argued here. It followed a long-lived episode of accretionary tectonics and signals an abrupt change in the dynamics of plate engagement. An example of such a switch is provided by Miocene contractional orogeny along the convergent margin exposed in Costa Rica that resulted from a change in plate kinematics from oblique to orthogonal convergence (Mescua *et al.*, 2017). As reviewed by these authors, many of the variables in subduction kinematics have the potential to induce contractional orogenesis including convergence rate and direction, inclination of the down-going slab, terrigenous sediment supply to the trench, and subduction of unusually young oceanic crust or that raised as an oceanic plateau. Given the continental scale of diachronous Tabberabberan orogenesis, the cause is likely to have been a step change in the kinematics of the oceanic plate subduction (Cawood, 2005).

Conclusions

The subduction complex that dominates the southern Mossman Orogen (Broken River Province) contains alternating quartz-rich and more labile turbidite assemblages associated with chert and mafic volcanic rocks. These rocks represent imbricated ocean-plate stratigraphy and are associated with ubiquitous mélange. Geochronology of detrital zircon from sandstone samples indicate a late Cambrian–Ordovician age for the quartz-rich turbidite association and a late Silurian–mid Devonian age for that of more labile character. The complex thus has a long history, spanning some 130 Myr.

Based on detrital zircon age spectra from more labile sandstone samples of Middle Ordovician–Middle Devonian age, sedimentary provenance of the accretionary complex during this interval was largely from a subjacent Ordovician to a Devonian Andean magmatic chain developed along an active continental margin inboard of the complex during this interval. In contrast, the age spectra for older (Cambrian–Early Ordovician) quartz-rich sandstone samples from the complex are dominated by Pacific-Gondwana (650–550 Ma) and Grenville (1300–900 Ma) clusters, reflecting a much more distant Gondwanan provenance as is characteristic of lower Paleozoic sedimentary rocks of the Tasmanides in general.

Older units of the subduction complex, characterised by quartzose sandstone, are structurally interleaved with younger units, characterised by more labile sandstone. This map pattern is attributed to underplating of the younger assemblage beneath the older, with subsequent out-of-sequence thrusting late in development of the complex disrupting its earlier age structure.

An abrupt change in plate dynamics in the Late Devonian produced regional-scale terminal deformation of the subduction complex and subjacent forearc basin within the southern Mossman Orogen. For convenience, this contraction is attributed to Tabberabberan orogenesis within the Tasmanides. Tabberabberan orogenesis is of Middle Devonian age in southeastern Australia and the age offset for its northern expression reflects diachronous contraction along the East Gondwana margin spanning an interval of some 15 Ma.

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Supplementary papers

Table A1. Geochemistry of mafic volcanic samples from the Wairuna, Pelican Range, Greenvale and Perry Creek formations (Withnall & Lang, 1993; unpublished data of A. J. Crawford).

Table A2. U–Pb isotopic data for detrital zircon from the Broken River Province.

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Figures and tables

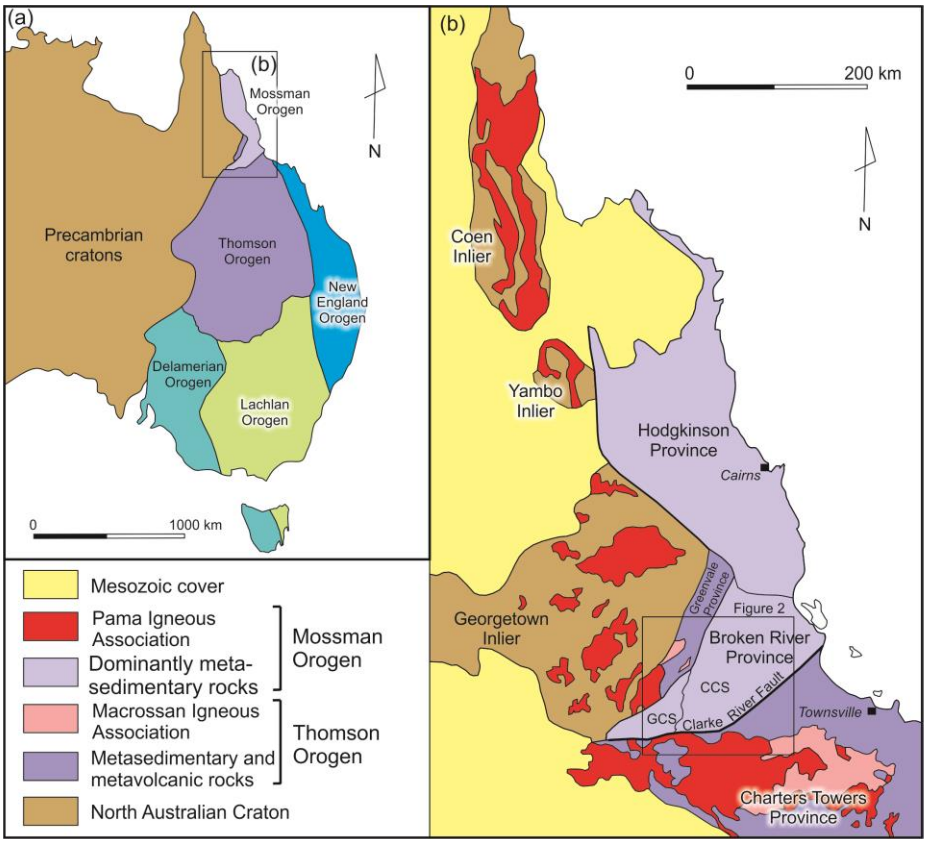

Figure 1. (a) Location of the Mossman Orogen in the various orogens of the Tasmanides in eastern Australia. (b) Context of the Broken River Province as part of the Mossman Orogen in the northern Tasman Orogenic Zone. The Broken River Province is subdivided into a southwestern Graveyard Creek Subprovince (GCS, forearc basin) and an eastern Camel Creek Subprovince (CCS, subduction complex). The adjacent Greenvale and Charters Towers provinces, parts of the older Thomson Orogen, and North Australian Craton (Proterozoic) host extensive plutonic rocks assigned to the Macrossan Igneous Association (latest Cambrian–Middle Ordovician) and the Pama Igneous Association (mid Silurian–Early Devonian). Cenozoic units are not shown.

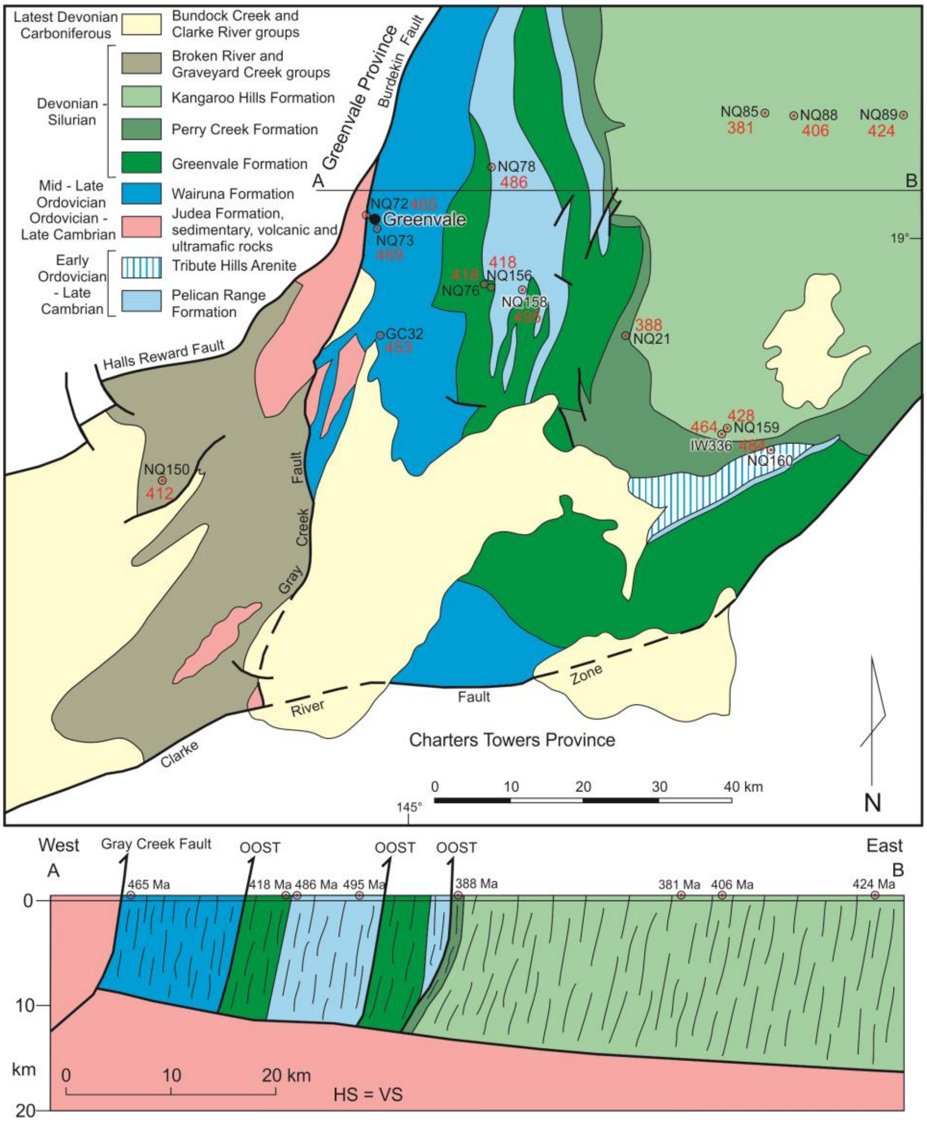

Figure 2. Geology of the Broken River Province showing rock units of the late Cambrian–Devonian subduction complex east of the Gray Creek and Burdekin faults, those of the related Silurian–Devonian forearc basin west of the Gray Creek Fault and sampling locations. Also shown are latest Devonian–Pennsylvanian successor basins that unconformably overlap these elements. Adjoining rock systems of the Charters Towers and Greenvale provinces are diverse and overlap in age with those of the Broken River Province. They unconformably underlie the forearc basin. Distribution of the Wairuna Formation is complicated in its western part by infaulted strips of unrelated rocks (not shown). Sample numbers shown in black and MDAs shown in red. MDAs

are projected onto the cross section A–B. Abbreviations: OOST, out-of-sequence thrust, HS = VS, horizontal scale = vertical scale. See Figure 1 for location.

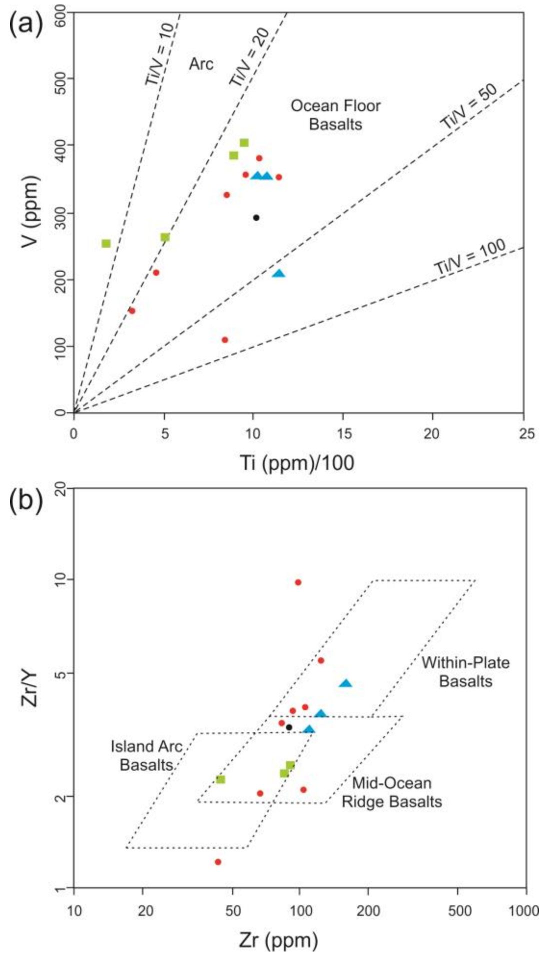

Figure 3. Discrimination diagrams based on the geochemistry of mafic rocks from units of the Broken River Province subduction complex: red, Wairuna Formation; green, Greenvale Formation; blue, Perry Creek Formation; black, Pelican Range Formation (supporting analytical data from Withnall & Lang, 1993 and A. J. Crawford unpublished are provided in Supplementary paper 2). (a) plot of Shervias (1982) and (b) plot of Pearce and Norry (1979). Most samples are of ocean floor affinity.

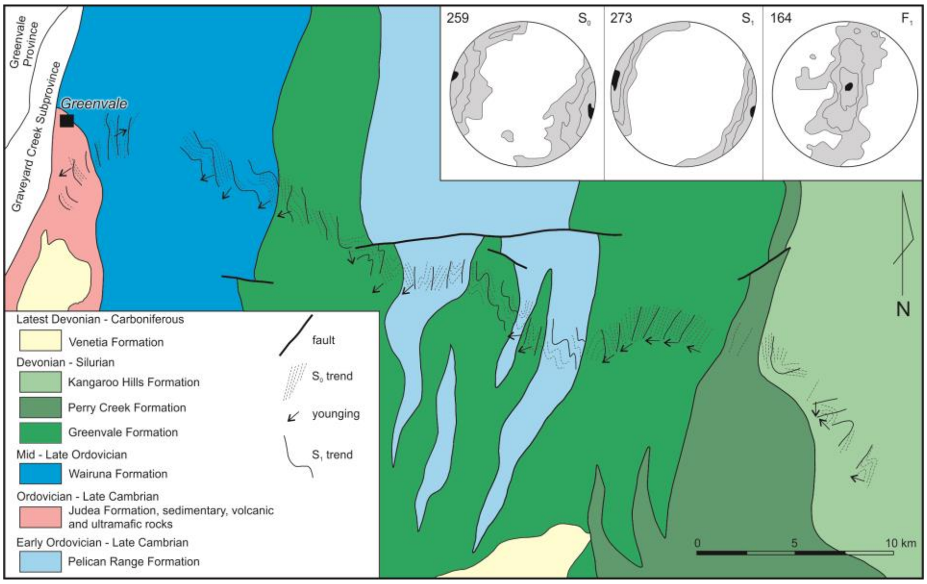

Figure 4. Structural data for bedding, slaty cleavage and slaty cleavage fold plunges for a traverse across the subduction complex. Its rock units share a common structural history, regardless of age, and show a dominance of west facing for bedding in all units. Modified from Henderson *et al.* (2013, figure 4.70); based on Arnold (1975) and Withnall and Lang (1992).

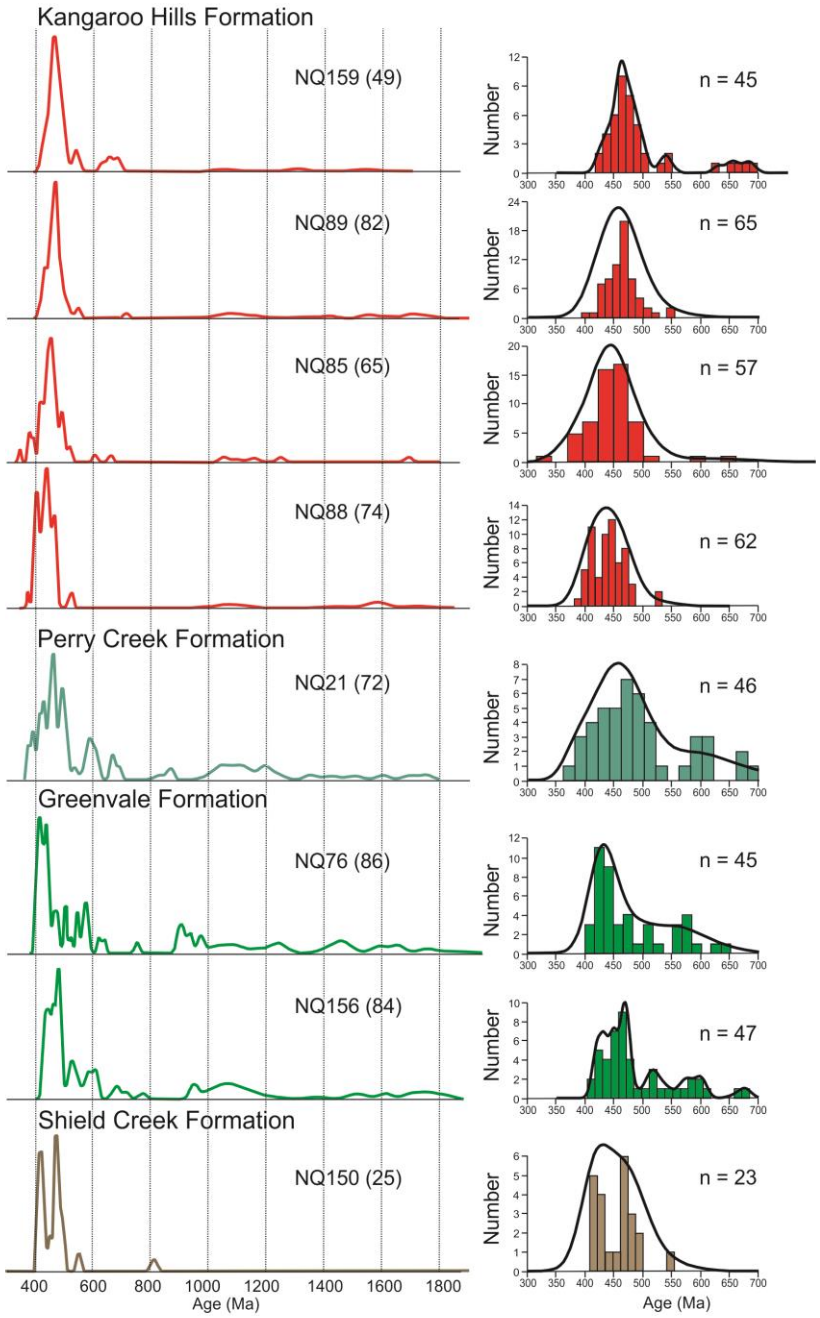

Figure 5. Relative probability distribution of ages for zircon grain populations of sandstone samples from the Greenvale Formation (late Silurian), Kangaroo Hills Formation (late Silurian–Middle Devonian) and Perry Creek Formation (likely Middle Devonian) and also for the Shield Creek

Formation (Early Devonian). The dominant age cluster for all populations is 500–400 Ma, matching the age of extensive granitoid plutons exposed on the periphery of the Broken River Province (see Figure 2). Histograms show the number of concordant analyses (n = number) for each sample in the range 700–300 Ma with the relative probability distribution (recalculated for subset) overlain in black.

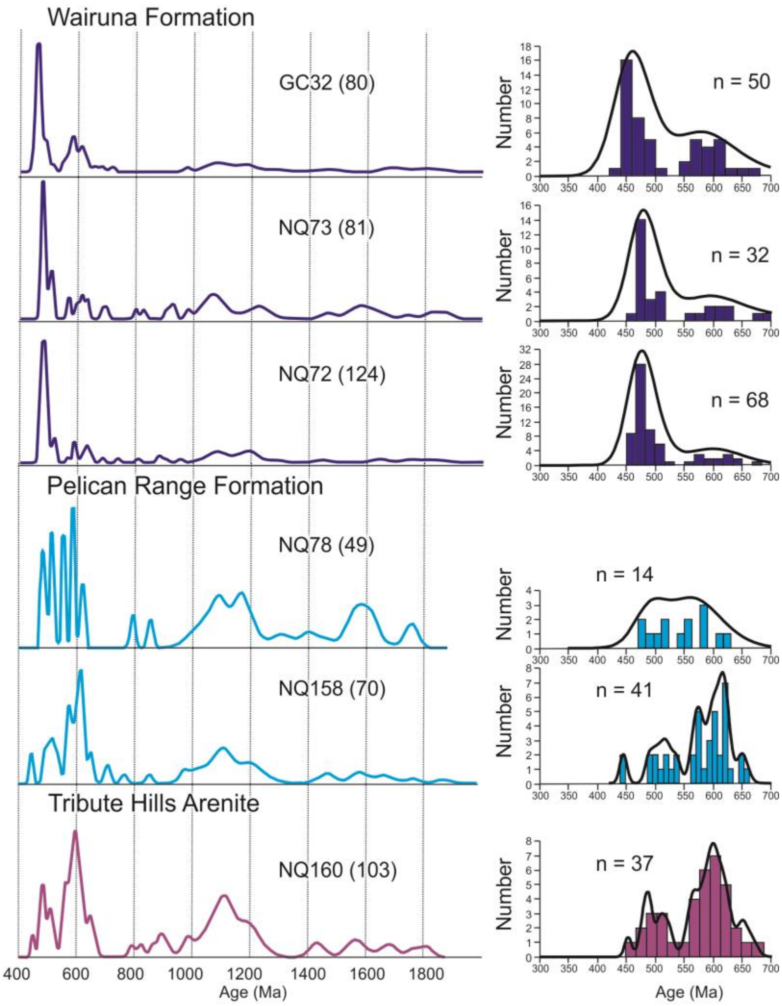

Figure 6. Relative probability distribution of ages for zircon grain populations of sandstone samples from the Wairuna Formation (Middle to Late Ordovician), Tribute Hills Arenite (earliest Ordovician) and Pelican Range Formation (late Cambrian–Early Ordovician). Histograms show the number of concordant analyses (n = number) for each sample in the range 700–300 Ma with the relative probability distribution (recalculated for subset) overlain in black. The dominant ages in the Pelican Range Formation and Tribute Hills Arenite represent the Pacific-Gondwana and Grenville clusters that characterise detrital zircon age spectra for samples of Ordovician age and older throughout the Tasman Orogenic Zone.

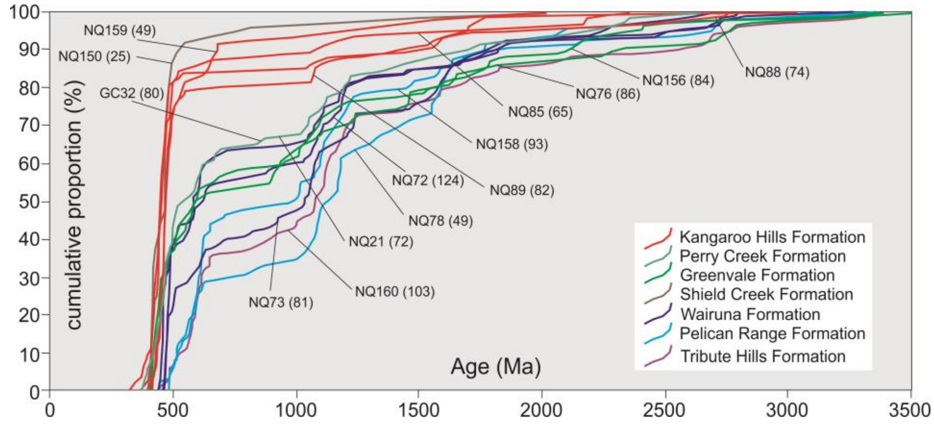

Figure 7. Cumulative proportion curves of age data for zircon populations obtained from the sandstone samples included in this study. For each curve, sample numbers, source formation denoted by colour, and the number of analyses represented (in brackets) are shown.

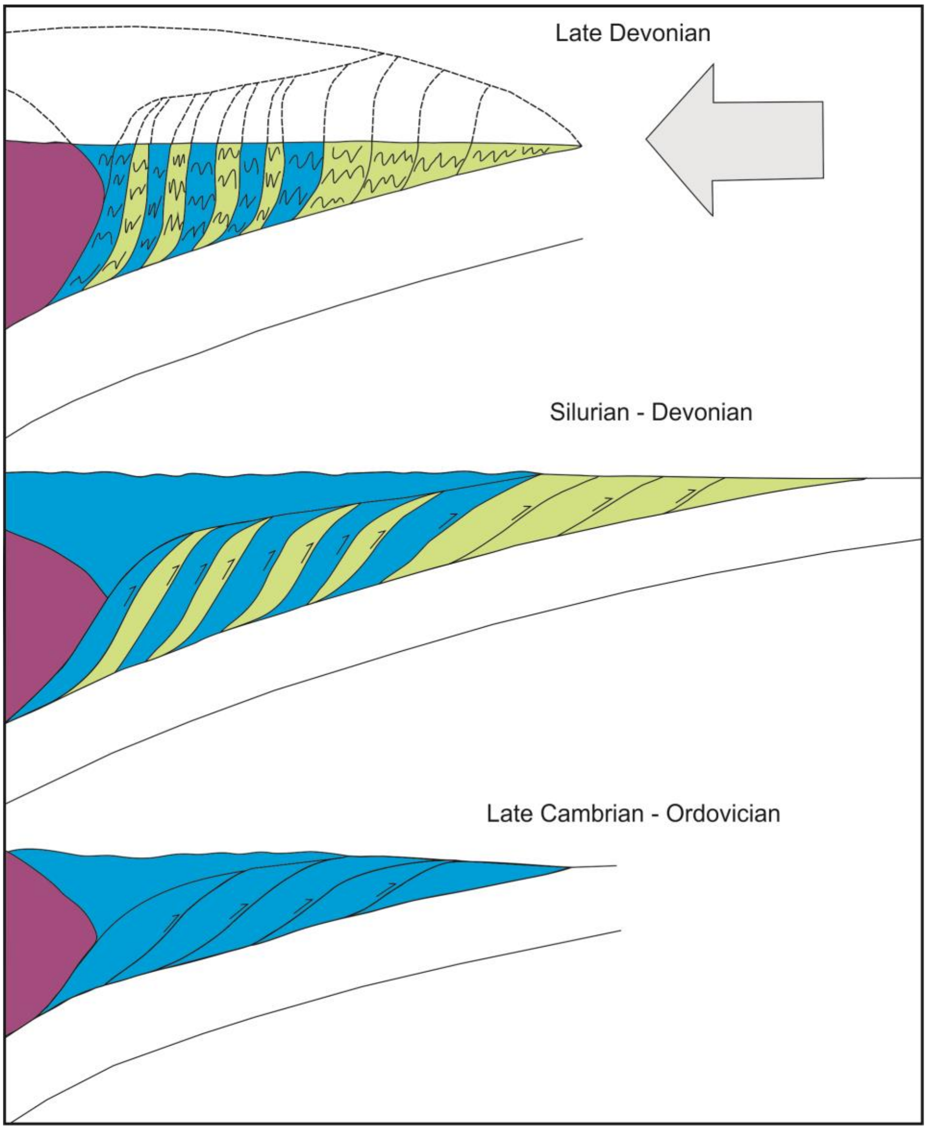

Figure 8. Schematic profiles showing the evolution of the Broken River Province subduction complex. Most of its history involved growth by underthrusting and reorganisation of its contents by out of sequence thrusting.

Table 1. Summary of lithological characteristics for formations mapped for the Broken River subduction complex.

Table 2. Samples analysed for detrital zircon age spectra with a summary of the analyses and the maximum depositional ages (MDA) derived from them (see text for details).

Table 1. Summary of lithological characteristics for formations mapped for the Broken River subduction complex.

	Latest Cambrian–Early Ordovician		Middle–Late Ordovician		Late Silurian–Middle Devonian	
	Tribute Hills Arenite	**Pelican Range Formation**	**Wairuna Formation**	**Greenvale Formation**	**Perry Creek Formation**	
Dominant greywacke type	Quartzose	Quartzose	Quartzose	Lithofeldspathic	Lithofeldspathic	Lithofeldspathic
Polymict conglomerate horizons			Rare	Uncommon	Common	Common
Limestone olistoliths					Common	Uncommon
Mafic volcanic bodies		Uncommon	Common	Common	Common	Rare
Chert lenses		Uncommon	Common	Common	Common	
Melange	Uncommon	Widespread	Widespread	Widespread	Widespread	Widespread
Pre-slaty cleavage folding	Uncommon	Widespread	Widespread	Widespread	Widespread	Widespread

Table 2. Samples analysed for detrital zircon age spectra with a summary of the analyses and the maximum depositional ages (MDA) derived from them (see text for details).

Sample	Grid ref (GDA94)	Unit	Lithology	Grain analyses	Accepted	MDA	Young outliers rejected
NQ72	289074 7897766	Wairuna Formation	Quartz greywacke	144	124	465 ± 2.4; MSWD 0.53; 14 grains	
NQ73	290201 7897688	Wairuna Formation	Quartz greywacke	90	81	470 ± 3.6; MSWD 0.22; 7 grains	
GC32	289636 7884958	Wairuna Formation	Lithic greywacke	90	80	453 ± 2.9; MSWD 0.66; 17 grains	
NQ78	303932 7907895	Pelican Range Formation	Quartz greywacke	58	49	inconclusive, 486 ± 18; MSWD 2; 3 grains	
NQ158	308089 7890065	Pelican Range Formation	Quartz greywacke	104	93	496 ± 6.7; MSWD 1.2; 4 grains	2
NQ160	340156 7871358	Tribute Hills Arenite	Quartz greywacke	109	103	484 ± 6.2; MSWD 0.69; 5 grains	
NQ76	303174 7890974	Greenvale Formation	Lithofeldspathic greywacke	99	86	414.6 ± 3.8; MSWD 1.0; 6 grains	
NQ156	303274 7890875	Greenvale Formation	Lithofeldspathic greywacke	91	84	418 ± 5.8; MSWD 0.33; 5 grains	
NQ21	320925 7887133	Perry Creek Formation	Lithofeldspathic greywacke	105	72	388 ± 13; MSWD 3.2; 5 grains	
NQ85	333874 7791619	Kangaroo Hills Formation	Feldspathic greywacke	95	65	381 ± 10; MSWD 2.8; 5 grains	1
NQ88	352705 7914534	Kangaroo Hills Formation	Feldspathic greywacke	79	74	400.6 ± 3.8; MSWD 0.52; 5 grains	1
NQ89	360300 7915158	Kangaroo Hills Formation	Feldspathic greywacke	105	82	424.3 ± 4; MSWD 0.78;	1

						8 grains
NQ159	334688 7874203	Kangaroo Hills Formation	Feldspathic greywacke	51	49	427 ± 8.1; MSWD 0.48; 4 grains
IWCR336	334170 7874170	Kangaroo Hills Formation	Feldspathic greywacke	20	15	464 ± 3.9; MSWD 0.27; 6 grains
NQ150	260566 7864377	Shield Creek Formation	Arkose	31	25	411.5 ± 5.5; MSWD 0.03; 4 grains